Interacting colour strings approach in modelling of rapidity correlations

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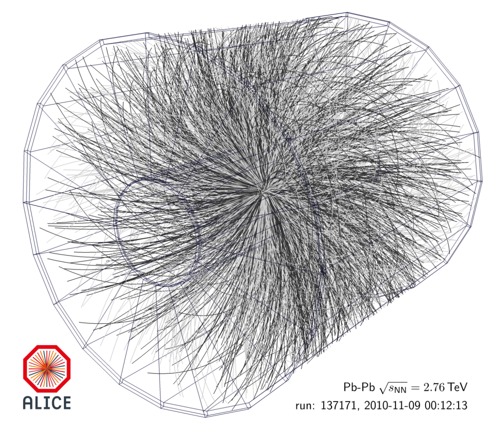
2. Monte-Carlo model development and tuning

3. Study of correlations: model results, ALICE data and PYTHIA simulations

4. Summary

Colour quark-gluon strings as particle emitting sources

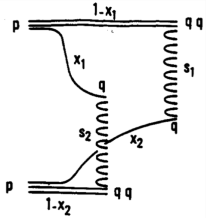
Why?



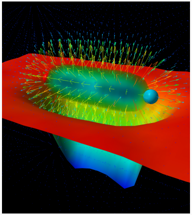
[https://cds.cern.ch/record/2032743]

- soft processes predominate in hadron collisions
- impossible to conduct the calculations in perturbative QCD regime
- the largest uncertainties come from the initial stages of the collisions
- phenomenological colour strings approach can deal with it!

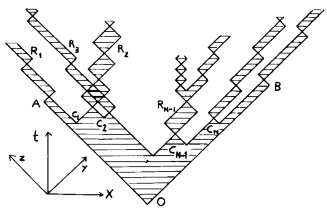
- non-perturbative Regge approach: a unitarity cut of the cylindrical Pomeron diagram $\rightarrow$ two-chain diagram $\leftrightarrow$ two strings formed
- strings stretch between flying outwards wounded partons and are formed by the colour field lines gathered together (gluon self-interaction)
- colour field energy grows with the distance $\rightarrow$ string fragmentation starts
- strings' remnants: colourless hadrons or new strings that still break with the further expansion



A. Capella, Phys. Rep. **236**, 225 (1994)



P. Varilly, Thesis, MIT (2006).



X. Artru, Phys. Rep. **97**, 147 (1983)

Monte-Carlo model development and tuning

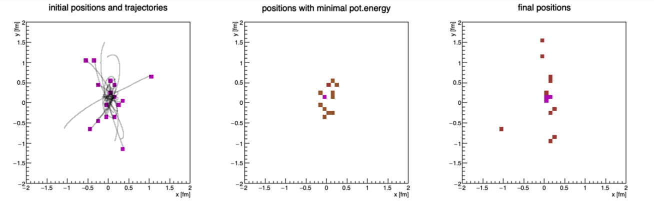
Transverse strings dynamics

We put strings in motion in transverse direction according to system of DE:

$$\ddot{\vec{r}}_i = \vec{f}_{ij} = \frac{\vec{r}_{ij}}{\sqrt{r_{ij}^2 + s_{\mathrm{string}}^2}} (g_N \sigma) m_\sigma 2 K_1(m_\sigma \tilde{r}_{ij}), \qquad (1)$$

where K_1 is a modified Bessel function [T. Kalaydzhyan, E. Shuryak, Phys. Rev. C 90(1), 014901 (2014)].

String evolution can be frozen at the conventional string fragmentation time $\tau = 1.5$ fm/c or at the moment τ_{deepest} with the global minimum of the potential energy of the system $\leftrightarrow$ fireball creation.



Example of 16 strings movement: left) initial positions and trajectories, middle) position at τ_{deepest}, right) positions at $\tau = 1.5$ fm/c.

Longitudinal strings dynamics

Initial strings ends' rapidities are defined by proton momentum fraction x_q (extracted from PDFs) carried by partons that form a string and for m_q we take current quark masses:

$$y_q = \operatorname{arcsinh}\left(\frac{x_q p_{beam}}{m_q}\right). \tag{2}$$

Afterwards, strings are shrinked in the longitudinal direction [C. Shen and B. Schenke, Phys. Rev. C 97, 024907 (2018)]:

$$\frac{dp_q}{dt} = -\sigma, \quad y^q_{\mathrm{loss}} = \operatorname{arccosh}\left(\frac{\tau^2\sigma^2}{2m_q^2} + 1\right). \tag{3}$$

τ - the time of system evolution in the transverse plane,
$\sigma = 0.16$ GeV/fm - string tension.

String fusion mechanism

Taking into account strings' density evolution in rapidity and transverse plane dimensions, we consider strings interaction in their final configuration:

- having finite size in the transverse plane strings can "overlap"
- their interaction changes the colour field density and modifies strings characteristics affecting particle production [M. A. Braun, C. Pajares, Inter. J. Mod. Phys. A 14, 2689 (1999)] :

$$\langle \mu \rangle_k = \mu_0 \sqrt{k}, \tag{4}$$

$$\langle p_T^2 \rangle_k = p_0^2 \sqrt{k}, \tag{5}$$

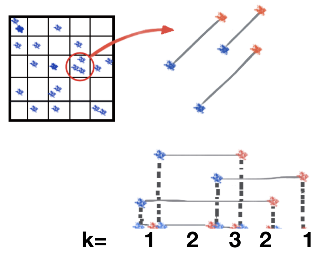
μ_0 - mean particle multiplicity per rapidity unit for an independent string,
p_0 - mean transverse momentum of particles produced by it,
$\langle \mu \rangle_k$ and $\langle p_T^2 \rangle_k$ correspond to the cluster of k fused strings.

Therefore, one expects lower multiplicity and higher p_T for interacting strings in comparison to the independent particle sources.

3-d fusion picture

We consider string fusion mechanism in the cellular version (in the transverse plane) for different slices of rapidity [V. V. Vechernin and R. S. Kolevatov, Vestn. SPbU Ser. 4, 11 (2004)].

If primary strings' centres lie in the same transverse cell, we do a projection in rapidity space to find the number of overlaps k. Thus, string clusters become shorter in y but more "powerful".



Schematic picture of the string fusion procedure. As example: 3 primary strings with $k = 1, 1, 1$ lying in the same cell result in 5 strings with $k = 1, 2, 3, 2, 1$.

Effective strings hadronisation

Event multiplicity:

- strings divided in y-direction into units of length ε with $\langle N_\varepsilon \rangle = \mu_0 \varepsilon \sqrt{k}$ and N_ε sampled from the Poisson distribution with this $\langle N_\varepsilon \rangle$
- string multiplicity $N^{\mathrm{str}} = \sum_\varepsilon N_\varepsilon$ and event multiplicity $N = \sum N^{\mathrm{str}}$

Particles' rapidities:

- for each of N_ε particles rapidity is sampled from Gauss distribution (mean = centre of the ε unit, variance = ε)

Particles' p_T is sampled from:

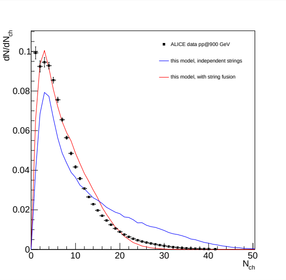
$$f(p_T) = \frac{\pi p_T}{2\langle p_T \rangle_k^2} \exp\left(-\frac{\pi p_T^2}{4\langle p_T \rangle_k^2}\right) \tag{6}$$

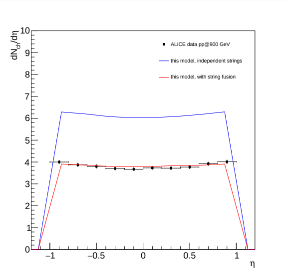
Particles' species:

- we consider π, K, p and ρ resonance $\rightarrow$ we know η for all the particles
- ρ decay probability depends on k^β with $\beta = 1.16[1-(\ln\sqrt{s_{NN}}-2.52)^{-0.19}]$

  [V. Kovalenko, G. Feofilov, A. Puchkov and F. Valiev, Universe 2022, 8, 246]

Model tuning: examples of comparison plots

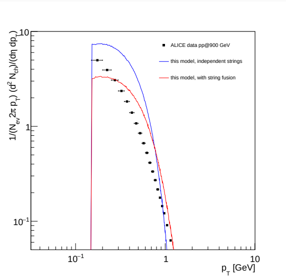


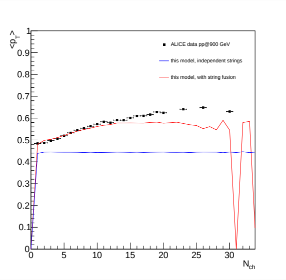


To tune our model we simultaneously fit different ALICE data on p+p inelastic interactions at $\sqrt{s_{NN}} = 900$ GeV

multiplicity distribution

η spectra





p_T spectra

$\langle p_T \rangle - N$ correlation

Study of correlations: model results, ALICE data and PYTHIA simulations

Quantities of interest

We study long-range correlations in terms of correlation coefficient that represents the slope of the correlation function defined in two pseudorapidity intervals ("Forward" and "Backward") separated by $\Delta\eta$:

$$b_{B-F} = \left.\frac{d\langle B\rangle_F}{dF}\right|_{\mathbf{F}=\langle\mathbf{F}\rangle} \tag{7}$$

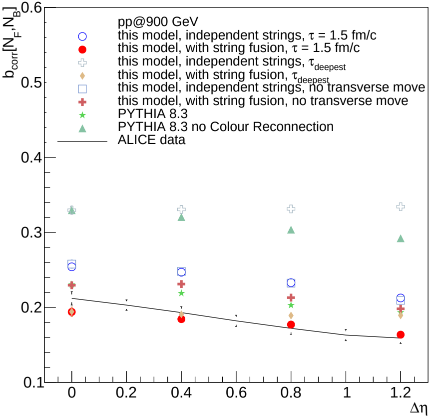
In normalised variables (to get rid of the experimental bias) for multiplicities N_F and N_B it becomes:

$$b_{\mathrm{corr}}[N_F, N_B] = \frac{\langle N_F\rangle}{\langle N_B\rangle}\frac{d\langle N_B\rangle}{dN_F} \tag{8}$$

And in the case of linear correlation functions, it transforms into:

$$b_{\mathrm{corr}}[N_F, N_B] = \frac{\langle N_F N_B\rangle - \langle N_F\rangle\langle N_B\rangle}{\langle N_B^2\rangle - \langle N_B\rangle^2}. \tag{9}$$

Multiplicity correlations via $b_{\mathrm{corr}}[N_F, N_B]$



Results for $b_{\mathrm{corr}}[N_F, N_B]$ as a function of the distance $\Delta\eta$ between Forward and Backward pseudorapidity acceptance intervals, where N_F and N_B multiplicities were calculated for inelastic p+p interactions at $\sqrt{s_{NN}} = 900$ GeV.
Particle selection: 0.3 GeV$/c < p_T < 1.5$ GeV$/c$.

Multiplicity correlations via $b_{\mathrm{corr}}[N_F, N_B]$: discussion

There are two groups of results:

① $b_{\mathrm{corr}}[N_F, N_B]$ for $\tau_{deepest}$ exhibits no dependence on $\Delta\eta$: colour strings stay long enough to impact into both F and B windows $\leftrightarrow$ strong correlation

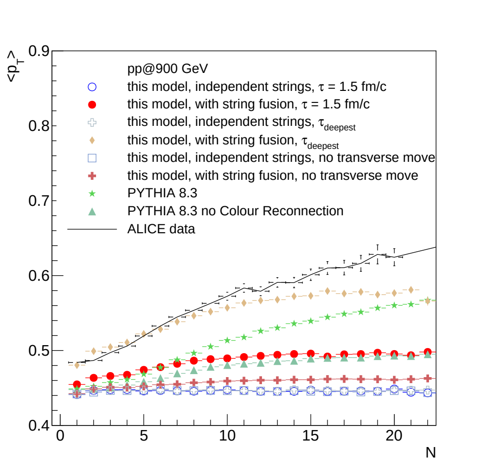
- ☞ result for interacting strings lies below one for independent strings due to the lower multiplicity caused by string fusion

② $b_{\mathrm{corr}}[N_F, N_B]$ for all the rest cases decreases with $\Delta\eta$: colour strings are shrinked already by y_{loss} so that they impact more independently in F and B windows the more they are separated $\leftrightarrow$ correlation falls off with $\Delta\eta$

- ☞ results for $\tau = 1.5$ fm/c and for the case without transverse strings dynamics lie on top of each other for independent strings
- ☞ for interacting strings results for $\tau = 1.5$ fm/c lie below the case without transverse strings dynamics due to the higher probability for strings to fuse and consequently lower multiplicity
- ☞ the same behaviour for PYTHIA: effect of colour reconnection $\leftrightarrow$ effect of our string fusion

$b_{\mathrm{corr}}[N_F, N_B]$ for $\tau = 1.5$ fm/c and interacting strings follows ALICE data

$\langle p_T \rangle - N$ correlation functions



Results for $\langle p_T \rangle - N$ correlation function calculated in $|\eta| < 0.8$ pseudorapidity acceptance with 0.3 GeV$/c < p_T < 1.5$ GeV$/c$ for inelastic p+p interactions at $\sqrt{s_{NN}} = 900$ GeV.

$\langle p_T \rangle - N$ correlation functions: discussion

① results for independent strings lie on each other and exhibit no dependence of $\langle p_T \rangle$ on N regardless the transverse strings dynamics

② $\langle p_T \rangle$ vs N with string fusion for fixed strings' positions in transverse plane shows a very slight (almost no) dependence $\leftrightarrow$ very rare fusion

③ $\langle p_T \rangle$ - N correlation is weaker for string evolving till $\tau = 1.5$ fm/c in comparison to the one for the largest density of strings at τ_{deepest} $\leftrightarrow$ again fusion probability

④ colour reconnection in PYTHIA plays similar role as our string fusion mechanism

Summary

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In general:

- we address the problem of initial conditions in relativistic p+p collisions
- the Monte-Carlo model of interacting colour strings as particle emitting sources that has non-uniform strings density over rapidity was developed
- it has rich 3-d dynamics of strings and string fusion mechanism, what makes it useful in the study of correlations

In particular:

- results on multiplicity and transverse momentum correlations for p+p interactions at $\sqrt{s} = 900$ GeV are presented
- string fusion mechanism gives similar effect for correlations as Colour Reconnection option in PYTHIA 8.3
- long-range correlations in the model comes from fluctuations in the number of long strings simultaneously in F and B pseudorapidity intervals
- short-range correlations are effectively implemented via the presence of short strings that independently impact in F and B pseudorapidity intervals

THANK YOU FOR YOUR ATTENTION!

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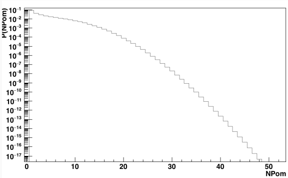
BACK-UP

Formation of colour strings

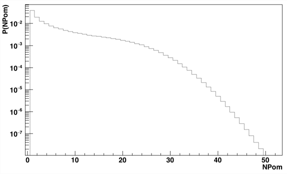
An event simulation starts with defining the number of colour strings as $N_{\rm str} = 2N_{\rm pom}$, $N_{\rm pom}$ comes from the pomeron number distribution function:

$$f(N_{\rm pom}) \sim \frac{1}{zN_{\rm pom}} \left(1 - e^{-z} \sum_{l=0}^{N_{\rm pom}-1} \frac{z^l}{l!}\right), \quad z = \frac{2C\gamma s_{NN}^{\Delta}}{R^2 + \alpha' \log(s_{NN})} \qquad (10)$$

[G.H. Arakelyan, A. Capella, A.B. Kaidalov, Yu.M. Shabelski, Eur. Phys. J. C26, 81 (2002)]



a)



b)

Example distribution of the number of pomerons for inelastic p+p interactions at $\sqrt{s_{NN}}$ = a) 900 GeV, b) 7000 GeV.

In our approach, $N_{\rm partons} = N_{\rm str}$ since we do not allow partons to escape the collision: all partons from two colliding protons should form strings.

Formation of colour strings

We prepare a large set of protons using PDFs to sample x_i [CT10nnlo set №1 by LHAPDF at $Q^2 = 1$ (GeV/c)^2] and demanding for each proton:

$$\sum_{i=0}^{N_{\text{partons}}} x_i < 1, \sum_{i=0}^{N_{\text{partons}}} e_i < 1 \tag{11}$$

where $x_i = \frac{p_i}{p_{\text{proton}}}$ and $e_i = \sqrt{\frac{m_i^2}{m_{\text{proton}}^2 \cosh^2(y_{\text{beam}})} + x_i^2 \tanh^2(y_{\text{beam}})}$.

To meet these conditions, we exchange partons in two random protons asking for the largest possible sum of x_i and e_i. If, after all the combinations, it is still less then 1, we create a gluonic cloud with $x_{\text{gcloud}} = 1 - \sum_{i=0}^{N_{\text{partons}}} x_i$ and $e_{\text{gcloud}} = 1 - \sum_{i=0}^{N_{\text{partons}}} e_i$.

For each string from N_{str} we sample a pair of partons from two random prepared protons providing that $S_x \geq 2m_\pi$, where $S_x = \sqrt{s_{NN} x_1 x_2}$. All N_{str} should be formed from these two protons. When impossible, we look for another pair of random protons.

Model tuning

To tune our model we simultaneously fit different ALICE data on p+p inelastic interactions at $\sqrt{s_{NN}} = 900$ GeV:

- multiplicity distribution [http://mcplots-dev.cern.ch/cache/plots/mb-inelastic-nch-General-PurposeMCs.Main-alice3-eta1.0-pp-900-.png]
- η spectra [http://mcplots-dev.cern.ch/cache/plots/mb-inelastic-eta-General-PurposeMCs.Main-alice1-pp-900-.png]
- p_T spectra [http://mcplots-dev.cern.ch/cache/plots/mb-inelastic-pt-General-PurposeMCs.Main-alice2-pp-900-.png]
- $\langle p_T \rangle - N$ correlation function [http://mcplots-dev.cern.ch/cache/plots/mb-inelastic-avgpt-vs-nch-General-PurposeMCs.Main-alice2-pp-900-.png]

Best results for free model parameters: $\mu_0 = 0.9$ and $p_0 = 0.4$ GeV/c.

Global model parameters:

- $g_N \sigma_T = 0.2$, $s_{string} = 0.176$ fm, $m_\sigma = 0.6$ GeV
  [T. Kalaydzhyan, E. Shuryak, Phys. Rev. C 90(1), 014901 (2014)]
- $\Delta = 0.139$, $C = 1.5$, $\gamma = 1.77\ \mathrm{GeV}^{-2}$, $R^2 = 3.18\ \mathrm{GeV}^{-2}$, $\alpha^{'} = 0.21\ \mathrm{GeV}^{-2}$ [V. V. Vechernin, J.Phys.Conf.Ser. 1690 (2020) 1]